Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

OBSERVATIONS ON THE METALLIC COMPOSITION

FOR

THE SPECULA OF REFLECTING TELESCOPES,

AND THE MANNER OF CASTING THEM:

Also a method of communicating to them any particular conoidal figure: with an attempt to explain, on scientific principles, the grounds of each process: and occasional remarks on the construction of telescopes.

BY THE REV. JAMES LITTLE.

READ, FEB. 4th, 1805.

THERE are but few things produced by the united effort of mechanical artifice and intellectual labour, which have done more honour to the ingenuity and invention of man, than the reflecting telescope; which has many advantages over any of the dioptrical kind, notwithstanding their improvement by achromatic glasses. It will bear a greater aperture, and may be made to magnify more, (as being more distinct,) in proportion to its length, than the others, as they are at present made; and its dimensions and powers are unlimited. What its excellence is, especially the Newtonian construction of it, has been proved by Dr. Herschell, to his own honour, and that of the age, and country, and patronage, which encouraged his labours. Accordingly, the persons, eminent for science and mechanical ingenuity, appear to have felt a peculiar and disinterested pleasure, in contributing to its improvement: and the late discovery of a metallic composition for the mirrors of it, which will bear as high a polish as glass, reflect as much light as glass transmits, and endure almost equally well, without contracting tarnish, is a farther encouragement to prosecute its improvement to perfection.

Among others, I had formerly, from admiration at its contrivance, bestowed some attention on the mechanism of this instrument: and, as it would have spared me some expence of time and trials, if any other person had previously suggested to me the hints, which I am to relate; I imagine they will be of use to others, in directing or assisting the course of their labour, in the same pursuit. I had also taken some pains, to understand the merits of the different constructions of this telescope: but, as this enquiry ended in a conviction, that the Newtonian form of it is the most perfect that can be hoped for; (it being the nature of its great author, to persevere in his researches, till he had arrived at a complete solution of his doubts, and comprehension of the subject;) so I have only to report what resulted from my experience in the mechanical fabrication of it, as to the method of casting the mirrors, and communicating to them the proper figure.

Before I had heard of the improvements of the Rev. Mr. Edwards, in the composition of the specula for telescopes, I had made many experiments myself with that view; which lead me to give full credit to his report of the superior excellence of that composition which he recommends: because I had found, that the qualities of hardness, whiteness, and indisposition to contract tarnish, necessary to a speculum, could not, by any admixture that I could hit upon, be produced, unless the metal were so highly saturated with tin, as to be excessively brittle; and because I found that this brittleness, however inconvenient in some respects, was necessary to render it susceptible of the highest polish: for no metal yet known, except steel, (which, from its disposition to rust, is unfit for this purpose,) will take as high a polish as glass will, unless it be more brittle than glass. And indeed this property is common to all substances which we know, that are capable of such polish: they must be very hard, and, as such, brittle; for the polishing powder employed would stick and bed itself in any soft metal, instead of cutting and polishing it.

From the result of my trials, I contented myself with the composition mentioned hereafter, as being in every respect sufficient for the purpose, and inferior to none in whiteness, lustre, and exemption from tarnish: for, as to the addition of silver, I found that, when used even in a very small quantity, it had an extraordinary property of rendering the metal so soft, that I was deterred from employing it: and unless it shall be found that, without this effect, it makes the metal less porous than otherwise it might be, or less frail and brittle, I am certain that it may, in every other respect, be dispensed with. I had no opportunity to try it, in the precise quantity Mr. Edwards recommends, (though I did so before, in very nearly that proportion,) since I first saw his memoir on that subject. Sir Isaac Newton made trial of a very small portion of it, and found the same effects from it as I experienced: but it is possible, that, if it were added in the just proportion discovered by Mr. Edwards, it would be an improvement, and useful ingredient, in the composition.*

I must observe here, that a metal, not liable to contract tarnish from the air, is otherwise susceptible of it accidentally; when there happen to be minute holes in its surface, caused by the air, or sand, &c. in casting it. Such cavities will be filled with the dust, or rusty solution of the brass, in grinding; which will, in time, become a sort of vitriol, and act on the contiguous parts of the speculum, producing a canker in it, which will spread, in form of a cloud of tarnish, around each cavity. In such a case, to prevent this, I would advise, to lay the mirror, as soon as polished, in warm water, and, after drying, while it remains heated, to rub it over with spirit-varnish; from which it may be cleansed, by a piece of fine linen dipped in spirit of wine. The varnish will remain in the cavities; and, by defending the impurities in them from the action of the air, will probably preserve them from becoming corrosive to the metal.

---

* Having read somewhere, that zinc and gold made the best speculum-metal, I tried it; and found, that the zinc was sublimed from the gold in fusion, and arose to the top in the crucible, forming a white, hard, spongy mass. The metal, called tutanag, is fit for specula, when melted with tin; but I am certain, that what I procured, under the name of tutanag, was a mixture of brass and copper, &c.; for the zinc, in the brass, rose from it, during the fusion, in white flowers.

From numerous experiments, of the qualities of different compositions, made by several persons, it appears, that no combinations, of any other metals or semi-metals, are fit for specula, except those of copper, brass, tin, silver, and arsenic. I tried no semi-metal, except the latter, which whitens copper, and unites intimately with it; because it is stated, in the treatise of the *Art of Assaying*, by the observant and accurate *Cramer*, that all the semi-metals rise in flowers, during the fusion: which would certainly make the metal porous. On this account, I would have rejected the brass, because of the zinc contained in it; but that it seemed to render the composition whiter, and less apt to tarnish, than it would be without it. It will have little tendency to rise in flowers, if the speculum-metal be fused, with the lowest heat requisite, and if the brass be of the best kind; because, in this, the zinc is more perfectly united with the copper, and both are purer. I used, for this purpose, the brass of pin-wire: and, because the quantity of it was only the one eighth part of the copper employed, which, I imagined, would receive too fierce a heat, if put alone into the melted copper; I first added to the brass, in fusion, about an equal quantity of the tin, and put the mass cold into the melted copper; supplying afterward the remainder of the tin, and then the arsenic; the whole being generally in the following proportion: viz. 32 parts best bar copper, previously fluxed with the black flux, of two parts tartar, and one of nitre, 4 parts brass, 16½ parts tin, and $1\frac{1}{4}$ arsenic. I suppose, with others, that, if the metal be granulated, by pouring it, when first melted, into water, and then fused a second time, it will be less porous than at first.

In this process, whatever metals are used, and in what proportions soever, the chief object is, to hit on the exact point of saturation of the copper, &c. by the tin. For, if the latter be added in too great quantity, the metal will be dull-coloured and soft; if too little, it will not attain the most perfect whiteness, and will certainly tarnish. It is too late to discover the imperfections of the metal, after the mirrors are cast and polished; and no tokens given of them (that I know) are sufficiently free from ambiguity. But I observed the following, which proved, in my trials, at first view, indubitable marks of the degree of saturation; and I think it fit to describe them particularly, as they have not, to my knowledge, been noticed by others.

When the metal was melted, and before I poured it into the flask, I always took about the quantity of an ounce of it, with a small ladle, out of the crucible, and poured it on a cold flag; and observed the following appearances.

First. If the metal assumed, in cooling, a lively blue, or purple colour, commonly intermixed with clouds, or shades of green or yellow; and if, when broken, the face of the fracture exhibited a silvery whiteness, as bright and glistening as quicksilver, without any appearance of grain, or inequality of texture; then the degree of saturation of the metal, with the tin, was complete and perfect.

Secondly. If the surface of the metal became of a dun or mouse colour, and especially if of a brown or red; and, when broken, the fracture exhibited a more yellow, or tawny hue, than that of quicksilver; then the quantity of tin in the composition was deficient, and it was necessary to add more.*

Thirdly. If the colour was an uniform dull blue, like lead, and, where broken, discovered a dull colour, with a coarse grain, like facetts; the due saturation was exceeded, and there was an over proportion of tin in the metal.

These colours would be more distinct, if a small quantity of the metal were cast in a flask, which had been previously smoaked, by a candle, made of resin mixed with tallow; in which way I used to prepare the moulds. I attribute the formation of the colours to this: that, as the calx of every metal has its own peculiar colour, so, the heat of the melted mass, calcining some of the particles on its surface, which are in contact with the air, these display the colour of the calces of those ingredients,

---

* This can always be done by degrees, and without any trouble, till the point of saturation is found; whereas, if too much tin were added at first, there would be a necessity for melting more copper separately, and repeating the whole process: and different specimens of copper will require different proportions of tin; so that the due quantity can never be known, *a priori*, but on trial only.

gredients which prevail in the composition. Whence, it may be expected, that, if the copper is the redundant metal, the mass will exhibit a reddish tinge, which is appropriate to the calx of copper; and, if the tin be prevalent, a blucish die ought to appear. Either of these colours, therefore, appearing unmixed, shews the redundance of that metal, to which each belongs. And, as brass, when cast alone, has always a yellow tinge, so, when these three colours are exhibited in a cloud-like mixture, they shew an equality and due proportion of their respective metals in the composition. When too large a mass of the metal is cast together, its intense and lasting heat calcines the surface so deeply, as (when exposed to the air) to obscure the colours; so that a small quantity will best serve to exhibit them.

As to the method of casting the mirrors, it has been directed, to leave the ingate, or superfluous part of the cast, so large, as to contain a quantity of metal, equal to that in the mirror itself; which would occasion a great waste of it, and render it not easy to cast, at once, more than one mirror in each mould; and even this might be done so injudiciously, as not to afford security against a miscarriage of the cast. But it will appear, that this great quantity of metal, and incommodious manner of casting it, are by no means necessary. However, a judgment cannot be formed, of what may be the safest and most eligible method for casting the mirrors, unless it be considered, what are the circumstances attending this operation, in the case of malleable metals; and how the management of speculum-metal, in this respect, must differ from that of them: since there must be peculiar difficulty in casting, in sand, a metal more brittle than glass.

When any fused metal is poured into the flask, the external parts of it, which are in contact with the mould, congeal and harden, sooner than the internal parts, and form a solid shell, filled with the rest of the metal, in a fluid state. This will, consequently, remain in a state of greater expansion, from its heat, than the external crust: and its particles will, in the act of shrinking as it cools, recede from one another, as being more easily separable, and cohere, on each side, with the particles already fixed and grown solid: by which means a vacuum will be formed in the middle, and this will be gradually filled by the superincumbent metal, which has been later poured in, and remains longer in a fluid state. But, when there is no more metal supplied, the void, which was in this way latest formed, remains unfilled; and then the shell of the metal, adjacent to the vacuum, as yet remaining soft, and unable to bear the weight of the atmosphere, resting on it, sinks, and is pressed down into the vacuum: by which means, a pit or cavity will be constantly and necessarily formed in the face of the cast, in that part of it which was last congealed; which cavity will commonly be larger or smaller, in proportion to the quantity of metal in the cast.

The event will, in this respect, be the same with speculum-metal, as it is, in the case of that which is tough and malleable: only that, as the former, in cooling, arrives sooner at its natural state of hardness and brittleness, its external solid shell will not bend, but break, and fall into the void part under it; and thus form cracks, or abrupt chasms, in the places, where tougher metals would contract only regular depressions. And also, when the body of the cast is small, or the mould is so damp or cold, as to congeal, not only the surface, but the substance, of the cast too soon, and thus prevent a gradual influx of the fluid metal, to keep the central part as distended, as the exterior shell was, when it became fixed; the farther contraction of the interior parts of this brittle, refractory metal, after it has become solid, will be apt to form rents in it, because its substance will not bear extension, without rupture.

It would be an obvious remedy of the above inconvenience, if there could be contrived a reservoir of fluid metal, to descend into the interior part of the cast, and fill up the void made in it, as fast, and as long, as it is forming by the contraction of the metal. Now, this is effected, by having a jet or appendage to the cast, of such a size, form, and position, as will be effectual to retain the metal, composing it, in a state of fluidity; and also to suffer it to descend into the interior of the cast, until all parts of the same become fixed, and incapable of receiving any farther influx of metal. For thus, all the imperfections, that would otherwise be in the cast itself, will now exist only in the appendage to it, which is a supernumerary part, to be afterwards separated from it. This appendage ought to be of the form of a prism, and as nearly that of a cube, as the operation of moulding it in the sand will permit; for, in this gross shape, the metal in it will be the longer cooling. It should be connected with that part of the mirror, which is uppermost in the flask, and joined to it by a neck, equal in thickness to the edge of the mirror, (but so posited, that the face of the mirror may project a little above it,) and, in breadth, about twice the thickness. This neck ought to be as short as possible, i. e. just so as to permit it to be nicked round with the edge of a file, in order to break off the prism from the mirror when cast: for thus the heat of the large contiguous body of the prism will keep the neck from congealing; which, if it happened, would stop the liquefied metal, in the prism, from running down into the mirror. And, to prevent this, the prism ought not to form directly a part of the main jet or ingate, by which the metal is poured into the flask; for so the jet would cool sooner than the large mass of the mirror, and bear off the weight of the atmosphere, which ought to press on the fluid metal in the prism underneath, and force it down into the mirror, to fill up all vacuities in it. Both the prism and the mirror, therefore, ought to be filled by a lateral channel, opening (from the principal ingate) into the top of the prism; which latter should be formed broad and flat, and not taper upward, like a pyramid, lest, by cooling where it grows narrow, it might form a solid arch, and oppose the pressure of the atmosphere. When it is fashioned, as here directed, and made of a bulk equal to a third or fourth part of the mass of the mirror, or even a fifth or sixth part, when the mirrors are of large size, there will ever be found, in the top of the prism, after the metal is cast, a deep pit or cavity, which contained the metal, that had ran down into the mirror, after the outer shell of the mirror, and sides of the prism, had become solid and congealed; and the mirror itself will be found perfect, without any sinking or cavity; which could only be formed by an injudicious disposition of the jet or appendage, permitting the metal in it to freeze sooner than the whole mass in the mirror, and thus stopping its descent into it. If several mirrors be cast together, in the same flask, there must be such a separate appendage made to each of them.

In this manner I have (without a failure in any) cast many mirrors of different sizes, and sometimes several of them together in one flask. But very small ones, such as the little mirrors for Gregorian telescopes, cannot be cast in this manner; for their masses being but small, they cool too quickly, to receive any additional infusion of metal; and their outer edges, suddenly forming a solid incompressible arch, the central parts, in contracting towards it on every side, separate, and are rent asunder. And this has happened, even when I cast them in brass moulds made red hot: on which account, I have been obliged to form them out of pieces of the metal, cast in long thin ingots or bars; which, by nicking them across with a file, could be easily broken into square pieces, whose corners could be taken off, and rounded in the same manner.

I do not repeat the other precautions to be observed in this process, which have been already so well and sagaciously described by the Rev. Mr. Edwards: but the circumstances above-mentioned, a prudent attention to which is, in my opinion, essentially necessary to the success of it, are not to be collected from any directions published on the subject that are known to me. And though particular artists may, by large experience, arrive at a sufficient knowledge in this matter, for their own practice; yet, to render that knowledge general, and to contribute, as far as I could, to the improvement of this instrument in any hands, being the design of this essay, I thought it necessary to state the above particulars fully; though I doubt not that these, as well as other matters of moment in the operation, are known to many, who chuse not to make them public. Thus the great skill, in the construction of the telescope, acquired by Mr. Short, seems not to have been transmitted to any successor.

I come now to speak of the most difficult part of the mechanism of this instrument, that of communicating a proper figure to the mirrors; on which depends the powers of the telescope, when its dimensions are given; for the manner of polishing them, to the highest degree of lustre, has been already well understood and described. They who have tried this part of the work, and know how inconceivably small is that incorrectness of form, which will produce grievous aberrations of the rays of light, will, I am sure, readily subscribe to the assertion, that '*hoc opus*, '*hic labor est*.' Methods have indeed been proposed for accomplishing it; but not a single hint given, that I know, of the *modus operandi*, or the grounds of these methods: insomuch, that, when I first tried to polish mirrors, I had no idea why any figure of them, different from that of a sphere, should result from the modes of polishing recommended. But, on my making the attempt, in the ways proposed by Mr. Mudge and by Mr. Edwards, I was surprised to find, that sometimes a spheroidal or other irregular figure, and sometimes (though rarely) a conoidal one, was produced by each: the cause of either being to me then unknown; and disappointment or success appearing to depend on mere accident, and not on the degree of pains and accuracy used in the process.

At length I began to suspect, that these variations, in the event of the process, (which will be hereafter accounted for,) arose from some property, not adverted to, in the pitch that covered the polishing tool; which material has been generally used for this purpose, of communicating a proper figure, as well as a high polish, to the mirror, since it was first recommended by Sir Isaac Newton; being commonly spread on the polisher, to about the thickness of a crown-piece, and then covered with the polishing powder; (the manner of doing which I suppose the reader to be acquainted with, as also with what has been made public on the subject, by Messrs. Hadley, Mudge, Edwards, &c.;) and I was confirmed in my suspicion, from the following reasons, after I had found them approved by many repeated and diversified experiments.

Pitch is a soft unelastic substance, which, as such, will suffer a permanent change of form, when it is made to sustain a degree of pressure sufficient to communicate an intestine motion to its particles: and this property directs us to consider, what may be the effect of the pressure of the mirror on it, when spread on the polisher, as to the figure it may then gradually acquire, during the operation of polishing, and the resistance and friction it will oppose to the mirror: for, by reason of the tenacity of its substance, it will resist a certain degree of pressure, without change of its form, but will yield to a greater pressure. But it is by its resistance the mirror is worn down and polished; if, therefore, that resistance be not uniform and equal, on the whole surface of the polisher, neither will the abrasion of the mirror be equal in every part; the consequence of which must be, that both will degenerate from an uniform curvature, i. e. from a spherical figure; the mirror from unequal friction, and the polisher from its mobility, by which it will adapt itself to the successive alterations produced in the figure of the mirror; their mutual action and reaction inducing a change in both.*

---

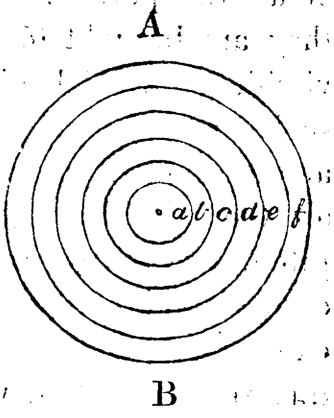
* This change, however, being so little, as to be imperceptible by the senses, and, in the imagination, referable to various other causes, it becomes necessary,

As the pitch is (in our present enquiry) to be considered as an homogeneous substance, we must suppose, that its resisting force, as well as that of the pressure of the mirror on it, are uniformly diffused over the surface of the polisher: and, from hence, it may not, perhaps, be easy to conceive, how the surface of the mirror could sustain from it any inequality of resistance and friction. In fact, these would be equal and uniform, in every part, if the pitch were a substance, either of perfect hardness, or perfect fluidity: but it will hereafter appear, that its consistence must not be so hard, as to render it incapable of any change of form; but, on the contrary, so soft, as to yield, in a small degree, to the pressure of the mirror: at the same time, opposing a resistance, sufficient to wear down and polish it: and the enquiry is, how that resistance is modified.

in order to establish the true cause, not only to deduce its existence and effects solely from reasoning on physical principles, but also to obviate other different conjectures that might be formed, by stating fully those circumstances that take place in this operation; and which, indeed, are necessary to be clearly understood in judicious practice. Both these ends cannot be answered, in a disquisition new and intricate, without a minute explanation: and this, I hope, will be received as my apology, for the prolixity of this account, which I would gladly have curtailed, if I knew how to do so, without making it less intelligible or useful to the practical optician. This class of readers will forgive any diffusiveness on a mechanical subject, if the perusal may tend to spare them the greater labour of fruitless experiments; or afford any hint towards conducting them more judiciously: and as for their use this paper was designed, I have adverted to such various matters as I thought most worthy their attention; and which yet have not been so fully and familiarly explained by others, as they ought to be, for the instruction of an artist.

Bodies of perfect hardness, such as glass, flints, &c. will not admit a total intimate change of their form, in all their dimensions, without a dissolution and permanent separation of all the particles composing their masses, (except when they are brought to a state of fusion by heat). But soft, viscid, semifluid bodies, such as lead, pitch, &c. will suffer such change, preserving the cohesion of their particles, yet, at the same time, undergoing a general intestine motion of all the particles among themselves: so that the coat of pitch, pressed, on each side, between the parallel surfaces of the mirror and polisher, will, by their force, be equally extended laterally in every direction; by which an equal quantity of motion will be communicated to all its particles: since no particles, except those at the extremities, can move, without protruding others, and these, the rest, successively, as if the mass were a fluid body.

But, though all parts of the surface of the polisher receive an equal pressure and motion, all do not exert an equal degree of resistance to that pressure: for those parts, that cannot move without displacing and overcoming the resisting tenacity of a greater quantity of the surrounding mass of pitch, than other parts do, must oppose the greater resistance to the mirror, as having that of the other parts superadded to their own. For ascertaining this, the force impressed, and the quantity of pitch, confining any annular tract of the polisher, should be computed. In the present case, where the coat of pitch is a thin equal stratum, of circular form, we need regard only its superficial dimension, and consider all parts of it as alike situated in the above respect, which are equidistant from the center, or from the outer edge of the polisher.



To this purpose, let the surface of the polisher, (supposed equal in size to the mirror,) be represented by the circle A B; and its area be conceived to be composed of an indefinite number of concentrical zones or annuli, *a*, *b*, *c*, *d*, &c. Each of these will sustain an uniform pressure, from the mirror, proportional to its area; because, the force impressed on the mirror, and its attraction to the polisher, is equably diffused on it. The areas of these annuli, taken separately, are the differences of the two circles, whose peripheries inscribe and circumscribe each of them; as the area of the annulus *d* (for instance) is the difference of the circles, whose radii are *a d* and *a c;* and they are, consequently, to each other, as the differences of the squares of their diameters, or as those of their radii; and the series of them, *a*, *b*, *c*, *d*, *e*, &c. taken, in order, from the center to the extremity, are strictly as a rank of figurate numbers proceeding from unity, viz. the odd numbers 1, 3, 5, 7, &c. But, since their breadth is supposed to be indefinitely small, they may be taken as proportional to their mean diameters or radii, i. e. as their distances from the center of the polisher; which distances will, therefore, represent the pressure on each annulus, and the quantity of motion communicated by that pressure; seeing it must be, as the number of particles the annulus contains that are moved; i. e. as its area.

But the resistance to the force impressed on any annulus, being as the quantity of pitch to be put in motion by it, will be different, not only as the annulus is nearer to, or farther from, the margin of the polisher, but different, also, as this has either one margin only, or two, i. e. when the polisher is entirely covered with pitch, or when it has a space left uncoated at the middle; which latter always is, and must be the case, when the great mirror of the Gregorian telescope is to be polished, which has a perforation at its center.

First. When there is no vacant space in the middle: the resistance to the several annuli will be as the circumambient spaces only; because, the pitch not being compressible, it is only into these, and not towards the center, it can, in yielding to the force or weight of the mirror, extend itself, by lateral motion: and the space, surrounding any annulus, is the difference between the circular area of the polisher, and that inscribed in the annulus; and is, relatively to the rest, measured by the difference of the squares of their radii, viz. of the distances of the edge of the polisher, and that of the annulus, from the center. But since, in this case, the bodies (of pitch) are unelastic, there can be no augmentation of motion; nor can the quantity of motion and action communicated, and, consequently, the resistance to it, and reaction, exceed that which is impressed: on which account, I imagine, that the resistance to the several annuli is to be taken as proportional to the pressures they sustain, and measured by them, i. e. by their magnitudes or areas, or the number of particles in them, to which a motion is imparted; which were stated to be as their respective radii or distances from the center: and, consequently, I suppose the resistance to be the inverse of this, or as the distances of the annuli from the outer edge of the polisher; which distances measure the direct resistance, or the quantity of pitch, to which equal motion, with that in the respective annuli, is communicated.

And from hence it follows, that, if a mirror, previously ground to a spherical figure, were to be polished on such a polisher as this: the resistance and friction of the pitch, being greatest, and increasing to a maximum at the center, and diminishing towards the extremity, would wear down and polish the mirror, most in the central part, and least towards its edges; thus giving to it a curvature, the reverse of a conoid, which it ought to have, and which it can never. at first acquire correctly, by any other mode of polishing, but that of wearing it most down (and thus reducing its curvature), towards its extremities.*

Secondly. When there is a hole made through the center of the polisher, or a void space left there, uncoated with pitch.†

---

* It will be hereafter shewn, for what particular purpose, solely, such a polisher may be employed.

† There ought always to be a hole made through the polisher, to prevent the confinement of air or water, near the center of it.

In these circumstances, the pitch will have liberty to expand itself (when yielding to the pressure of the mirror), towards the center, as well as the edges of the polisher: and, as the resistance and friction, in any annular tract of it, is as the direct extent of pitch, bounding it on either side, it follows, from what has been laid down, that it will encrease in any part, as the distance of the same annulus encreases, from each extremity of the coating of the polisher; and will be in a ratio compounded of the distances, from the interior and exterior margins of the pitch. So that, if the breadth of the polisher between these margins were, (for example,) 5 inches: then the pressure and friction in the middle tract, equidistant from the outer and inner edges, would be, to that prevailing at the distance of half an inch from either margin, as 6¼ to 2¼, (nearly as three to 1;) and the same, at proportionate distances, in polishers of any other size; which unequal pressure could never produce, in the mirror, a regular curvature of any species; and, in the spaces nearer to the margins, the inequality of pressure would be still greater. Whence may be conceived the impossibility of figuring mirrors correctly, on polishers disposed in this manner, without some remedial contrivance; whether the face, or area of them, be of a circular shape, as directed by Mr. Mudge and others, or oval, as proposed by Mr. Edwards: for the mirror would be thus least reduced, and left of a spherical form, at the middle and edges; and be worn down, and hollowed into a different and irregular curvature, in the intermediate tract.

For these inconveniences, however, arising from the unequal friction of the polisher, there are the following easy and adequate remedies; which will, in the sequel, be more fully explained, and applied as in practice, to effect the degree of curvature, or any correction of the same, which may be requisite.

First. Since the curvature of the mirror ought to be gradually reduced towards its edges, which can only be effected by an increase of friction in the corresponding part of the polisher; and that this latter effect is to be produced in any part of it, by enlarging the surrounding coat of pitch: it follows, that, for this purpose, the breadth of the polisher must be enlarged above that of the mirror; and this in the same degree, as the curvature of the mirror is to be diminished: so that the polisher is to be of greatest breadth, for a mirror of an hyperbolic, and least, for one of a spherical figure. This, however, is to be done, under the limitations hereafter mentioned.

Secondly. To preserve the regular gradation of curvature towards the middle of the mirror, the uncoated space, at the center of the polisher, should be contracted to a certain limit, which will be defined; though, for the reasons above-mentioned, it can never be filled up altogether.

Thirdly. Where the resistance and friction of the pitch, in any tract on the face of the polisher, is computed as above, or found in effect, to be too great; it may be lessened and regulated, in any degree, by cutting, out of that part of its surface, some of the pitch, at proper intervals, in narrow channels or furrows: the number and depth of which ought to be proportioned to their distance from the edges of the coat of pitch directly, and to the reduction of curvature, proper to the corresponding parts of the mirror inversely, and should be in a ratio compounded of both; for, by these cavities, the continuity of the pitch being dissolved, its resistance, depending thereon, may be modified at pleasure.

In this manner may the polisher be so disposed, as to communicate a correct figure to large mirrors, and even to those of smallest size. Now, whatever success may have attended the efforts of other persons, in communicating a proper figure to the *great* speculum, (especially Mr. Short, whom I have manifold reasons for believing to have been among the most eminent opticians, as well as artists, that have laboured in the improvement of this instrument;) I have not heard, that any method has been proposed, of communicating, to the *little* mirror of the Gregorian telescope, any other than a spherical form, which yet may in this manner be done. And it must, in this telescope, be a thing most desirable to accomplish; especially when its size and aperture is so great, that it would be difficult to impress, on the extensive surface of its great mirror, (merely by the small alteration of figure, which could be produced, in the delicate operation of polishing,) the degree of change, from its prior state of spherical curvature, which would be requisite; since the defect of form, in this mirror, may, in these cases, (as will be shewn,) be easily compensated, in the figuration of the little mirror. For the greater size of this latter, in such instances, will render it capable of more steady handling and motion, and more equal pressure; and so more manageable, and susceptible of a correct figure, in proportion as the encreased magnitude of the great mirror renders it unmanageable: which is, plainly, a great advantage, in the fabrication of this telescope; whose mirrors will thus, in the cases where it is most especially necessary and desirable, admit mutual correction and compensation for each other's defects.

The principles, or physical causes, operative in this process, as above stated, seem to be incontrovertibly evident; and, as I am not aware of any paralogism admitted in the reasoning upon them, I must suppose, that a mode of operation, conformable to these principles, is the thing chiefly requisite to ensure success. In this view, I have attempted to conduct the process; and, as the almost insuperable difficulties attending it are felt, even by those whose inventive powers and resources ought to afford the highest hopes of accomplishing the object, and yet disappoint them in their attempts at high perfection;[*] so I, among others, may be allowed to state the difficulties, that, to my apprehension, occurred in the enterprize, and to obviate objections; as, from hence, there may be suggested some hints, to facilitate or abridge future labour to others, or to prevent hopeless trials.

---

[*] Sir Isaac Newton, who had himself laboured in this undertaking, of polishing the concave mirror of his own telescope, and with such talents for the work, and such success, as to discover that method of doing it, which has, to this day,

I must observe, then, that different effects must necessarily follow, from using, in the process of polishing, pitch of a softer or harder consistence. If the pitch be of a

temper

---

day, been followed, observes, (to use his own words,) that "optic instruments "might be brought to any degree of perfection imaginable, provided a re"flecting substance could be found, which would polish as finely as glass, and "reflect as much light as glass transmits, and the art of communicating to it "a parabolic figure be also attained. But there seemed (*said he*) very great "difficulties, and *I had almost thought them insuperable*, when I farther con"sidered, that every irregularity, in a reflecting superficies, makes the rays "stray five or six times more out of their true course, than the like irregu"larities in a refracting one; so that a much greater curiosity would be here "requisite, than in figuring glasses for refraction..... &c.

"But, having afterwards thought on a *tender way of polishing*, proper for "metal, whereby, as I imagined, *the figure would also be corrected to the last*, "(i. e. the utmost,) I began to try what might be effected in this kind; and, "by degrees, perfected an instrument..... &c..... and afterwards another "one."

The tender way of polishing, which Sir Isaac Newton here mentions, was, (as he afterwards described it in his Optics,) to cover the polisher with pitch: and he declares, that he imagined the *figure*, as well as the *polish*, would, by means of this, be perfected. I cannot help thinking, that this extraordinary man, who was born to anticipate others in invention, as well as discovery, had the same ideas as are here detailed, though he did not explain, nor, perhaps, succeed in, the application of them in practice: for he states, (in his Principia,) that a spherical mirror will reflect the oblique pencils, issuing from the extremities of the field of view, as truly as a parabolic one, and seems to despair of effecting a more correct figure.

temper quite hard and unyielding, no part of the surface of the mirror can be made to suffer a higher degree of friction than the other parts of it, unless these latter parts be elevated and detached from the face of the polisher, and disengaged from contact with it; because, in this case, both mirror and polisher are supposed to preserve their general shape regular and unaltered: and, therefore, the contact, and, consequently, the friction, must be either complete and equal, on the whole surface, or none at all. For, if we suppose, that, by the wearing down of the mirror towards the extremities, it is made gradually to change its spherical form, the part of its area, so abraded and diminished, cannot subside into a state of actual contact with the polisher, unless the other parts of it are elevated and disengaged from the polisher, at the same time; or unless it may be imagined, that the particles, worn off the mirror by friction, are applied and adhere to the corresponding parts of the polisher, so as to raise and augment its surface, just as much as that of the mirror becomes depressed and reduced. If this effect could be supposed to take place, it would follow, that, in every variety in the direction of motion in the mirror, the friction must tend to wear down the edges, rather than the middle of the mirror; because the motive force is always applied to a part of the handle to which the metal is fastened, raised more or less above the surfaces in contact. The effect of which must be, to communicate to the foremost or advancing half of the mirror's surface, a pressure downward, on the face of the polisher, equal to the force expended in moving the mirror forward; and thus to abrade and reduce the several parts of the mirror's surface, proportionally to their respective distances from the center; by which its curvature will be made to approach to that of a parabola, by its wearing down most towards the edges: and this, whether the motion be conducted in lines diametrically across the polisher, or with round strokes; so as that its center should describe, every time, a little circle, about the center of the polisher. This is, however, entirely on the supposition, that the edges of the polisher become raised, by the adhesion of the dust worn from those of the mirror: for, if this were not the case, but that the polisher were to retain its spherical form, while that of the mirror was altered, the contact could not be general between two surfaces of dissimilar shape. If these adhered together in one part, they must be dissevered in another; and the force, necessary to separate them in this latter part, which can never be greater than that required to move the mirror forward, must yet be more than equal to the force of cohesion, in the part of the mirror, which, in each stroke, is to be disengaged from the polisher. This pressure is found, in the case of bodies in contact, to be incomparably greater than the weight of the atmosphere, which is equal to about seventeen or eighteen pounds on every square inch of the surface of the mirror: and, when this latter is brought so near that of the polisher, as to suffer friction from the powder bedded in it, their mutual attraction will amount to a much greater force than is requisite to move forward the mirror; no part of which can, therefore, be disengaged from the polisher, nor, consequently, be unequally worn down, so as to produce, in its surface, a form different from a spherical one, or from that of the polisher.

This reasoning and conclusion will equally stand, whether it be supposed, that the force of cohesion is confined to the very surfaces in contact, or extends to a little distance from them, diminishing in the duplicate, or any other ratio of that distance; and that the bodies are not wholly removed out of the sphere of attraction, when there is a small interval between them. For, as this force is greatest at the very surface; so, the bodies in contact cannot be disjoined at all, to the smallest distance, but by a force superior to the whole cohesive force.

It may, perhaps, be imagined, that the pressure of the atmosphere ought to be taken into consideration, and be added to the force of cohesion, which keeps the surfaces in contact with each other. But this pressure acts as much upon the coat or plate of water, which must be interposed between the surfaces of the mirror and polisher, as upon these surfaces themselves: and, because the pressure, upon any part of a confined fluid, is propagated to the whole of it, in every direction; so, the weight of the atmosphere, resting on the edges of this fluid plate, tends as much, by the interposition of the same, to buoy up, and force asunder, the surfaces resting on it, as it does to compress together these surfaces, by its action on themselves; and exerts itself equally to prevent their approach on one side, as their recession on the other. I conceive the agency of these forces to be this: that the plate of water is so strongly attracted by the surfaces nearly in contact, as to be kept from running off, and has its outer edge exposed to the weight of the air; whose pressure is thus communicated to all the particles of the water, and, by its mediation, to the contiguous surfaces of the mirror and polisher. And, though all these are really compressed together, by the surrounding atmosphere, yet I conceive that this does not hinder their gradual separation from being effected: because, as fast as that separation takes place on any side, the air and water rush in between the surfaces, to fill up the vacuity, as it is formed; and no farther resistance arises to their disjunction, than what is owing to the viscidity of the fluid interposed, and to the force of cohesion: which latter acts, in this case, quite different from any external force of compression; and prevails, as I apprehend, to a small distance from the surface, diminishing in the ratio of some high power of that distance.[*]

And

---

[*] If it were supposed, that the force of cohesion is confined to the surface of bodies, and acts only in the state of actual contact; it would be hard to conceive, why a drop of liquor should ascend, in a conical glass-pipe, whose narrow end was elevated: since the drop ought, on this supposition, to be attracted as much by the surface below, as by that above it; and its weight ought to make it descend: and there would be nothing to make it spread beyond the space of contact which it occupies: whereas, if

the

And hence I suppose, that the weight of the atmosphere is wholly inefficient, in keeping the mirror and polisher in mutual coherence, when any liquor of perfect fluidity is between them; and that the force of cohesion acts alone to this effect. Accordingly, it is found, that, when the polisher is so much wetted with water, that there is formed a continuous plate of this fluid between it and the mirror, an additional force, sufficient to squeeze out the water interposed, becomes requisite to bring the surfaces into actual contact, and to produce so much friction between them, as will serve to wear down and polish the metal; which process will be found, in these circumstances, to advance very slowly and irregularly. And, on the contrary, when so little water is applied to the polisher, that it is only made damp, and scarce wetted, (i. e. when there is not a continuous body of liquid interposed between it and the mirror,) then its contact with the metal will be so intimate and strong, that the latter will polish very quickly. For then their surfaces approach within the sphere of the attraction of cohesion: insomuch that, if all moisture were suffered to evaporate, the mirror and polisher would cohere so firmly, as not to permit any friction, or even a separation of their surfaces, and the polisher would be destroyed; for then the weight of the atmosphere, also, would be superadded,

---

the attraction extends, directly in right lines, to a distance from the sides of the pipe, the composition of their forces ought to make the drop ascend, and spread itself in its course, as it happens in fact.

superadded, when no fluid is interposed: all which shew that their cohesion, when a fluid does intervene, is not caused by the pressure of the atmosphere.

Agreeably to this, the sagacious Newton directs, that, toward the end of the operation, no more moisture should be applied to the polisher, than what it will contract, from the operator's breathing on it. Indeed, a person, who has formed a just conception of his genius and intense application of mind, and considered the hints and precepts he has given in this work, can hardly doubt, that he could, and, perhaps, would, have furnished a theory of the rules and method of this whole process; had he not imagined it would, at that time, be regarded as a matter of too little importance, to deserve so minute an explanation, which must be necessarily prolix, and seem unworthy of him, who was occupied in more sublime speculations.

From this it follows, that, when the pitch is of unyielding hardness, it will not, in any mode of polishing, communicate to the mirror the desired shape, if the dust, worn from the mirror, does not alter the shape of the polisher. And, as this seems not likely to happen, so I was not surprised, that my efforts, to effect the desired figuration of the mirror, by using very hard and refractory pitch, failed of success.

And there is this inconvenience, moreover, in the use of such pitch, viz. that it makes so great resistance to the sinking and bedding of the polishing powder in it, that the particles of the powder, however fine it may be, will, on any fresh application of it, or when any grains of it are accidentally dislodged from the pitch, roll about loose on the polisher, and scratch the face of the mirror, so as to destroy the polish before given; thus making any fresh application of the powder inadmissible, unless the pitch were to be softened by heating it, which would destroy its former figure, and render the operation uncertain and tedious. It was to allow the polishing powder to fix itself, without rolling loose on the polisher, and to suffer all its particles, however different in size, to sink in it, so as to form an even surface, that Sir Isaac Newton, in his sagacity, employed a coat of pitch on the polisher, as a soft substance, that would yield to the powder, when impressed on it by the mirror, and not afford such resistance, as to make it fret the face of the metal; and also as a substance endued with another property equally necessary, that of being perfectly unelastic. For no elastic substance will ever communicate an exquisite polish to a metallic speculum, though it would to glass, crystal, or jewels; because no metal can be cast, perfectly free from small pores: and any elastic substance, if employed to polish it, would insinuate itself, together with the polishing powder, into these pores, and wear down their edges in such a manner, as to convert every pore into a long furrow or cavity; which would occasion the destruction of the whole surface of the metal, as was truly observed by Sir Isaac Newton. And thus it appears,

pears, that, to make the pitch too hard and refractory, would be to destroy every property in it; which renders it eligible in this operation.

If the positions, before stated, be well founded, it seems to follow, that the desired change in the mirror, from a spherical to a conoidal figure, can only be effected, by a change in the shape of the polisher, gradually accommodating itself to the alteration, produced in that of the mirror, during the process of polishing. Nor, indeed, can it well be conceived, how the mirror could alter its spherical form, if that of the polisher remained unaltered; for a conoid could never, in the usual way, and without a partial separation of the surfaces in contact, be polished on a segment of a sphere, nor even on that of a conoid, if, during the friction of their surfaces, the center, or vertex of the one, were to be moved to any considerable distance from that of the other. So that the strokes, in polishing, must never ultimately be carried so far, as to remove the center of the mirror to too great a distance from that of the polisher; even though its surface were so hard, as to preserve its figure unaltered by the pressure of the mirror.*

---

* For the several reasons above-mentioned, I am inclined to think, it will be very difficult to discover a method, different from that here explained, of communicating, at the same time, a perfect figure and polish to a speculum. It is plain, that Newton could think of no better; though I imagine that, in this instance, he tried his inventive powers with those of Des Cartes, who had published a method (in theory elegantly geometrical) of figuring optic glasses.

Agreeable to these positions, I found, in my trials of polishing mirrors in the common way, by straight or round strokes of the mirror, on the polisher, that the operation was

glasses. And I cannot dissent from those, who think this was the method employed by Mr. Short, with such success, in figuring the mirrors of his telescopes; I mean a conduct in the operation, sagaciously adapted to the properties of the pitchy coating of the polisher.

It must be obvious to the reader, that none of the remarks or directions, contained in this essay, can be meant to apply directly to the polishing any speculum, whose magnitude is too great, to admit of being moved on a polisher, of equal size with itself. Where the friction, and force of cohesion, of such large surfaces in contact, and the weight of the mirror, exceed the motive power that can be employed, a polisher, of less extent than the whole surface of the mirror, must be applied, to traverse, in succession, the several parts of it; and the motion must be given, not to the mirror, but to the polisher. Instruments of far less enormous magnitude than Doctor Herschell's great telescope, are *sui generis*, and require particular methods of polishing the mirror adapted to their size. For such, no person should presume to propose any method, which he has not approved in practice: though, as the general principles here laid down, are, with due accommodation, applicable to a polisher of any shape or extent of surface; it should seem, that, if such great mirrors could be polished by a regular and uniform motion, their polishers might be made such segments or sectors, &c. of the area of each respective mirror, and of such breadths in different parts; and the furrows, made in the coating of pitch thereon, of such number, proximity, and depth, as to afford, in the tract of the motion of each part, a degree of pressure and friction, reciprocally proportional to the degree of curvature, proper to each concentric zone of the mirror's surface; which would tend to produce the desired figure, so far as a polisher, covered with pitch, could be made instrumental to this purpose. For, though the size and shape of the polisher were to remain unaltered, yet its resistence and abrading power might be considerably modified, by varying the number and depth of the furrows, made in the pitch which covers it. And the effect of a process, thus conducted, will be commensurate to the time it is persisted in.

was more easy and successful, when I used pitch of nearly the common consistence, than when I employed such as was made very hard, by long boiling it, or by the addition of much resin. Such softer pitch will admit more than one application of the polishing powder, without scratching the metal, or spoiling its previous polish; by which means, the process will be more expeditious. It will instantly accommodate itself to the successive alterations in the form of the metal; as this, by wearing down towards its edges, gradually changes, from a spherical, to a conoidal shape: and it will promote this effect, by opposing a greater resistance to the metal, and greater friction towards its extremities, when its previous disposition on the polisher has been judiciously provided, in the manner before explained.

But, to fulfil these intentions effectually, a certain kind of motion, of the mirror on the polisher, must be carefully observed, during the operation: for, as the softer pitch will continually yield, and sink under the pressure of the metal; so, the form of the polisher, degenerating in every stroke, must be recovered, and preserved correct. According to the principles before laid down, the face of the polisher must be considerably larger than that of the metal, in order to afford a greater resistance to the speculum, towards its extremities: so that, as the metal covers only a part of the polisher, if the former were to be confined in its motion, the pitch, sinking under it, would expand itself laterally, and become heaped up suddenly, around the tract of the mirror's pressure; which must, therefore, to obviate this, be so conducted, as to traverse, in quick and regular succession, every part of the polisher, in order to recover the regularity of its figure as fast as it becomes vitiated. And this is effected in two ways: either by enlarged circular strokes of the metal, brought considerably beyond the edges of the polisher, in order to repress, towards the center, the pitch, which had become raised near its edges; or by strait diametral strokes, across its surface, in every direction, successively: either of which will tend to preserve the figure of the polisher, and, consequently, of the mirror, nearly spherical. As, however, a spherical figure is not that which is ultimately intended, so these modes of conducting the process are to be pursued only till the mirror has acquired a sufficient polish, and a figure nearly spherical: and then, in order to give it a parabolic or hyperbolic shape, the motion of the mirror, on the polisher, should be such, as that the center of it may describe a spiral line round the center of the polisher, by enlarging the circular strokes, till the edge of the mirror arrives at the edge of the polisher; and then contracting the motion gradually, till the mirror returns to the center, in the same spiral course. By which means, any sudden and irregular elevation of the pitch, beyond the place of the mirror, will be prevented; while, at the same time, it will become regularly elevated, from the center

center to the outer edge, in the form of a conoid, and thus be adapted for communicating the same figure to the mirror.

I have been led to adopt and practise this method of polishing mirrors, by the train of reflections and reasoning herein described; and with sufficient success, for its unreserved recommendation. In one particular, it corresponds with the method published by Mr. Mudge, in the Philosophical Transactions, viz. in the direction of the motion used in polishing the mirror. But this seems to have been prescribed by him, without any respect to the properties of mobility and inequality of friction, in the pitchy coating of the polisher; which things he has not noticed. And yet, as any sort of motion, without a proper regard and adaptation to the qualities of the pitch, would be ineffectual, it is here attempted to supply that defect; because no method can be rightly pursued in practice, nor its success be uniform, nor any figure already given to the mirror be altered, if those artists, who would follow it, are ignorant of the principles and agency on which it is really founded. For, in every process of so subtil and delicate a nature, some untoward accidents and circumstances must occur, which will grow above the control and correction of any person, who is not aware of the secret causes from whence they arise. In such cases, the practice will be as imperfect as the theory is.

It has been above explained, how the middle zone, or tract of the polisher, equidistant from its inner and outer edge, when there is a void at the center, will oppose a greater degree of friction to the mirror, than the other parts of the polisher. And, to prevent the unequal wearing of the mirror, by the increased action of this zone, it will be proper, that, agreeable to the methods of prevention of this effect before-mentioned, there should be circular furrows indented in the pitch within this zone, more or fewer, according to the size of the mirror, and the designed degree of its curvature; in order that the pitch may subside into the furrows, and thus the resistance and friction in that tract be diminished. This will be very easily accomplished, by putting the polisher on the arbor of a lathe, and cutting out some of the pitch in circular grooves, with a small and sharp concave turning chisel, wetted with water, in which some soap has been dissolved. And this may be performed and repeated, if necessary, without any injury to the surface of the polisher, if it be previously wetted, to prevent the splinters of the pitch from sticking to it; which may be washed off, by a soft brush or pencil, from the polisher, it being immersed in water.

Since, in the Gregorian telescope, the defect of figure or curvature, from that of a conoid, in one of the mirrors, may be compensated by a contrary curvature in the other; and since, in either of the mirrors, whose breadth is given, the degree of variation in its figure, from that of a sphere, ought to be so much the greater, as its focus, or radius of curvature, is shorter; it will, on this account, be far more difficult, to effect a proper figure of the small mirror in this telescope, than of the large one; because the former must be a greater segment of the sphere, than the latter. For which reason, instead of making the one of an elliptic, and the other of a parabolic form, I imagine it would (with the exceptions before-mentioned) be more proper to rest content with a spherical form in the little mirror, (by which means, several of these latter, being fastened, with cement, beside each other, on the same handle, might be accurately and easily ground and polished together, on one tool and polisher, made sufficiently large); and to employ the great efforts on the large mirror, in rendering it of an hyperbolic form; which is not at all more difficult than it is to make it parabolic: for, on account of the small extent of surface of the little mirror, it is very difficult to govern and regulate its motion and pressure, so as to communicate to it any certain figure, if polished by itself singly; as it must be, when it is to be of any other than a spherical form. Yet, even this may, by an intelligent and dexterous artist, be accomplished, to a considerable degree of perfection, in the manner above-mentioned, as I have repeatedly experienced; though the process is much more easy and certain, in figuring the large mirror (under that limitation of its size before intimated): for the greater the surface to be polished is, the less will any inequality of pressure, in the operation, alter the form of the mirror, or the polisher; such inequality, being a part only of the motive force employed; and the more extensive the surface is, the less proportion does the motive force bear to the force of cohesion, which tends to preserve an uniformity of pressure in the mirror, and of figure in the polisher. And I believe it is on this account, rather than that of preventing aberrations of the rays of light, from a supposed spherical shape of the mirrors, that telescopes of greater apertures and foci are more accurate; the larger surfaces of their mirrors having a tendency, during the operation of polishing, to preserve the regularity of their figure. For, let the aperture of a telescope be ever so large, with respect to the focus of the great mirror; yet, when the object is very remote, the central part of the field of view (the rays of light from which fall parallel to the axis,) ought to appear perfectly distinct, if the metals were wrought up to the correct figure of conoids: and the vulgar doctrine of aberrations, which relate only to spheres, is entirely inapplicable. The only standard, for the measures of the apertures and foci, is the degree of ingenuity in the workman, who fabricates the instrument. There are many defects in figure, beside a spherical form of the mirrors; and it happens but too frequently, that a telescope is very indistinct, from a bad figure of them, though that figure is the nearest to a conoid of any regular curve: for this is often the case, when the central, the extreme, and the intermediate parts of the mirror, successively and separately exposed to receive the light from the object, appear to have the same focus. And this mostly occurs, when the mirrors are small; certain tracts, or portions of their surface, being more worn down, by the grinding or polishing,

ing, than others, arising from the difficulty of preserving an uniform pressure during the operation, and, consequently, a regular figure of the polisher.

Another method, different from that now described, of communicating to mirrors a parabolic form, has been discovered by the late Rev. Mr. Edwards, and published in the Nautical Almanack, for the year 1787. He recommends, to make the edge of the polisher the periphery of an ellipse; so that the face or area of it may not be round, but oval: the shortest diameter of the ellipse being equal to that of the mirror; and its longest diameter to be to the shortest, as 10 to 9. And he affirms, that a mirror, finished on such a polisher, will prove to be of a parabolic form; if the process be conducted, by employing, throughout the operation, straight strokes of the mirror, diametrically across the polisher, in every direction. Now, in the method recommended by Mr. Mudge, whatever kind of motion be used, in bringing the face of the mirror to a polish, the parabolic form is directed to be acquired, only by a circular motion in polishing: Mr. Mudge having declared, that the effect of such straight strokes would be, to produce no other than a correct spherical figure in the mirror. Here, then, are opposite motions and declared to be productive of contrary effects, proposed by two very intelligent artists, with a view of promoting the same effect; the only difference being this, that, in the one case, the face of the polisher

is

is supposed to be round, and in the other, oval: a difference that a person may well imagine to be (as it really is) of very little importance; and he may be easily led to suspect, that the presumed effect of either mode is only imaginary; that a spherical figure of the mirror has been mistaken for a parabolical one; or that, if the latter has been produced, it may have been, not by method, but by chance; and he may naturally distrust any rule or method advanced for this purpose. Thus, when different instructions are given, by different persons, without any reasons or explanation assigned as the foundation of them, the whole rests on authority; authorities clash, and then the worst may be followed, or all be rejected; and, for want of a guide, an uncertain practice be adopted. It is for this reason, I have judged it necessary here, (as also in former essays, made public,) to be very minute, in attempting to investigate the grounds of any method to be pursued, and the principles of action, in the operation of the instruments I am treating of.

I have made a trial of the method of polishing, proposed by Mr. Edwards, with attention to all the circumstances, which he directs to be observed; and, from the result, I have reason to believe, that his method is a good one, and will, if judiciously applied, produce as correct a figure of the mirror, as, perhaps, any other, yet made public. But, whoever will attentively investigate the nature of the operation, will, I think, cease to wonder,

der, that modes of conducting it, seemingly so dissimilar, tend to the same effect; and perceive, that the contrariety is not real, but merely apparent.*

For, in either method, it is not the direction of the motion employed, nor the shape of the area of the polisher, which, in reality, produces a conoidal form in the mirror; but a gradual alteration in the curvature of the face of the polisher, by the yielding of the pitch, under the pressure. And, therefore, when any part of the area of the polisher, whether it be round or oval, is more extended than that of the mirror; the pitch, moving laterally, will become elevated, and its curvature lessened, in that part. So that, in a polisher of oval shape, whose conjugate diameter is equal to that of the mirror, the pitch will ascend and accumulate, in the part, which lies without the circular area of the mirror, inscribed in the ellipse. The extremities of the mirror will, therefore, be worn down, when each part of them is made in rotation, by straight strokes across the polisher, in the transverse diameter of the ellipse, to traverse that part of it, which circumscribes the circle; and, by such strokes made twice, directly in that diameter, and oftener obliquely, in each rotation of the mirror, as the operator moves round the polisher, during the process, the regular shape of the polisher is preserved. But it is easy to conceive, that the same effects would follow, though the polishing were conducted, not by straight strokes across, but by round strokes, in a spiral direction, as above-mentioned. And I am doubtful, to which of these motions the preference should be given; or whether they ought not to be interchangeably used, to produce the most elaborate form in the mirror; as also, whether this method, of Mr. Edwards, is better than the former, by Mr. Mudge, above described. For I have been deprived of leisure and opportunity (by the war, and public troubles, during the French invasion and the rebellion; in which, most of my instruments, for such purposes, were lost, in the plunder and destruction of my house,) to prosecute the experiments, which might have enabled me to speak with more precision; and which I would have done, from the desire I had, to contribute to the perfection of so noble an instrument as the reflecting telescope.

---

* In the methods of figuring the mirrors, published by Mr. Mudge, and by Mr. Edwards, it is stated by Mr. Mudge, that he frequently, during the process, applied to the polisher a concave tool, which he calls a bruiser; by which he must have preserved, or recovered, the figure of the polisher, and, consequently, of the mirror, that otherwise must have become vitiated, by the unequal resistance of the pitch; and Mr. Edwards made furrows in the coating of pitch, on his polishers. It is to these circumstances, and not to the direction of the motion employed, or the elliptic area of the polisher, that, I can think, was owing the success, attendant on their methods: the bruiser being necessary, to supply the defect of furrows in the pitch; and the oval form not essential, when there were such, duly disposed, and also the polisher of proper size, &c. as here directed.

I know, that both methods will, in judicious practice, produce the desired effect; but this effect will be limited, in degree of perfection, and sometimes frustrated, when the causes and circumstances, that operate in it, are unknown. In either method, and with a polisher of round or oval shape, it is indispensably necessary, that there should be furrows made in the coating of pitch, (to allow it to subside, in regular gradation, from the middle to the edges,) by indenting it, either in squares, as is usually done, or in circular channels; both which must be renewed, as they become filled up and obliterated; which will always happen soonest in the middle zone or tract of the polisher, between the center and outer edge, whether the furrows be circular or longitudinal: and, if this be not done, the regularity of curvature would not be preserved in the mirror, or the polisher. But, since there is no obstacle to the subsidence of the pitch, near its outer edge, and its inner edge, when there is a void space at the center, I believe the furrows ought not to be made there, but in the intermediate space only. And I am of opinion that it is, from the judicious disposition of these furrows, the most correct shape of the mirror is to be acquired; whether the polisher be round or oval, or the pitch hard or soft: for I found, that, in Mr. Edwards's method, and with pitch, even as hard as he recommends, the channels made in it were, towards the end of the operation, nearly obliterated, in the middle zone of the polisher. But this will not happen so soon, nor so dangerously, with hard as with soft pitch; nor will the correction of the impaired shape of the polisher be so difficult, when it is of an oval, as when of a circular area: there being, in the former case, less of irregular surface in it, to be reduced; and a more steady, uniform, and simple motion, in grinding, may be pursued; which, as it will admit of a less degree of expertness and sagacity in the artificer, will be more commonly attended with eminent success.*

The consistence of the pitch is, in this business, an article of the first importance. Soft pitch will give to the polish a higher lustre, and will less expose the face of the mirror to scratches: but, if it be too soft, the mirror will sink in it, like a seal in soft wax; and the figure of the polisher cannot be preserved, nor the furrows in it, from being defaced. It must, therefore, be always harder than common pitch is, in a mean temperature of the air in this climate. And, after the polishing powder is bedded in it, (which must at first be laid on so copiously, that the pitch may not rise up to the surface, between the particles of it,) and when the mirror has been worked on it a little time, then all the loose particles of the powder ought to be washed off, from the edges and furrows of the pitch, with a sponge or brush, (made of fine hair,) under water, that no grains may get on the surface, and injure the polish. And, if this be attended to, and the pitch be a little softened by heat, when the powder is first applied, it may be used of a consistence hard enough, without inconvenience: but, if it be made so hard, as not to sink at all, or expand itself, under the mirror, I believe it will never communicate to it a perfect figure.

---

* I imagine, that a polisher, whose area is of an oval form, would be better adapted to the formation of a parabolic, than an hyperbolic curvature, in the speculum; and that the latter will be most correctly formed by a polisher, whose area is nearly circular. For, in order to make the speculum hyperbolic, the longest diameter of the oval polisher must be considerably greater than the shortest one, i. e. than the breadth of the mirror; as will be evident, from a consideration of the circumstances I have endeavoured to explain. And, as the mirror must be carried, by the strokes in polishing, to the extreme verge of the polisher; so, when it is to traverse it, in the direction of its longest diameter, it will have its center or vertex removed too far from that of the polisher, to acquire from it a true conoidal figure. Either, therefore, the face of the polisher should be round; or, if it be oval, it ought to be rendered a less eccentric ellipse, by having its shortest diameter greater than that of the mirror, which will allow the extent of the polisher to be reduced, by contracting proportionably its transverse diameter; i. e. it must be brought nearer to a circular figure. For the objection, mentioned by Mr. Edwards, to a round shape of the polisher, when it is to be considerably larger than the mirror, viz. " that it makes the latter grind perpetually into a segment of a " larger sphere, and by no means of a good figure," I apprehend to have chiefly arisen, from an omission, in those who tried it, to make furrows in the pitch, in the proper tract, on the surface of the polisher; which, if it had been done, would have produced, not a spherical, but a conoidal figure.

From what has been here laid down, it must be obvious, that, by diminishing the size of the polisher, whether it be of a circular or elliptic shape, the curvature of the mirror will be brought nearer to that of a circle; and, by enlarging the polisher, the curvature will approach to that of an hyperbola, when the precautions here given are observed. Both these may be done, by spreading the pitch on the polisher, to a greater or lesser extent.

In the Gregorian telescope, the excess of curvature, in the great mirror, may be remedied, by a defect of it in the little mirror, and vice versâ. It must be desirable, to a fabricator of this instrument, to understand why this is so; and how a change in the curvature may be effected: for an artist cannot well execute a project, the design of which is to him unknown; nor improve by trials, even repeated, if they are made in the dark. I apprehend, that, in this kind of telescope, the mirrors are commonly selected, out of a number finished of each size, as they happen to suit each other: and, if there should be but few pairs in the assortment, whose irregularities compensate one another, few good telescopes will be produced. This would be less frequently the case, and the Gregorian telescope be more improved, if a more certain method were known, of giving, to each pair, their appropriate figure at first, or of altering it in either, where it is defective. Perhaps persons, not much versed in optics or geometry, may be assisted, in discovering the evil, and the remedy, from the following remarks; which are given in words, in order to dispense with a diagram.

The curvature of the circumference of a circle is uniform in every part, being (in an arch of it, of a given length) so much the greater, as the radius is smaller, and vice versâ. But the curvature of the ellipse, parabola, and hyperbola, is not uniform, but continually diminishes, from the vertex of these curves, (which answers, in the present case, to the center of the mirror,) to the extremity on each side: but it diminishes less in the ellipsis than the parabola; and in this than in the hyperbola. So that, if we suppose a bow to be bent, at first, into an arch of a circle, and, when gradually relaxed, to become, towards its extremities, more and more straitened, as it unbends, while the curvature, at the very middle, remains the same, it will successively form these three curves, in the above order. And, if concave mirrors had the same curvature with them, they would have the following properties.

If the speculum be of a parabolic form, rays of light, falling on it, parallel to its axis, or issuing from a luminous point in the same, so very distant, that they may be regarded as parallel, will converge, by reflection, to one point in the axis; which point is the focus. The same is nearly true of rays coming from luminous points not far from the axis, or lying in a very contracted field of view, so as to make but a very small angle with the axis: the rays, coming from each single distinct point in the object, are converged to so many single distinct points in the image, formed at the focus of the mirror. Hence, the excellence of a parabolic mirror, for the larger speculum of the Newtonian or Gregorian telescope.*

---

* But, because a parabolic mirror reflects, to one point, rays, that fall on it, parallel to its axis, it follows, that it will not converge, to a point, rays, that are diverging or inclined to its axis. The former, (if the point, from whence they radiate, be in the axis of the mirror,) would be reflected from any line, drawn diametrically across the mirror, in a caustic curve double and cuspidated: the latter, (being in the same plane in which is the radiant point, infinitely distant, and the axis,) would form a curve nodated. So that the excellence of a parabolic mirror is for viewing remote, but not near objects. And a person might thus be deceived, who would judge of the goodness of a telescope, only from its rendering print legible, at a small distance, from whence the breadth of the great mirror would subtend an angle of sen-

If the mirror be of an elliptic, or oval, curvature, rays, issuing from single points, in, or extremely near to one of its foci, and falling on it, (such as the rays proceeding from the single points in the image, formed by the parabolic larger speculum,) will be converged to so many single distinct points, in the other focus of the elliptic mirror. Hence,

---

sible magnitude: for the pencils of rays that issue, diverging from each point of the printed letters, will be reflected, by the central part of the mirror, to a focus nearest to it; and the rays of each pencil, that fall on the exterior annuli of the mirror, will be reflected to points more remote from it. So that if, in the Newtonian and Gregorian telescope, the great mirror were of the correct figure of a parabola, and the little mirror, of the latter, were that of an ellipsis: and, if either telescope were adjusted to distinct vision, when the innermost zone only of the great speculum is exposed to the light; yet, the object would be indistinct, if seen by the rays reflected from the outer zone, unless the little mirror were removed farther from the great one. Hence, a spherical mirror is better than a parabolic one, for viewing very near objects; and neither of them can be equally adapted for viewing these and very remote objects. The distinctness of the telescope is, therefore, best proved, by directing it to the stars: if it shews, clearly, the fasciæ, on the disk of the planet Jupiter, or the ring of Saturn, it will deserve to be approved of. I have ground and polished, in the manner here described, the mirrors of a little Gregorian telescope, of nine inches focus, which shewed these objects most distinctly; and I could not afterward, with much greater pains, execute another one, (neither indeed did I ever see one,) of that size, of equal accuracy: which served to convince me, of the exquisite correctness required in the figure of the mirrors, and of how great perfection the instrument is susceptible. Telescopes have been recommended, for their enabling persons to read gilded letters, at a considerable distance: but this is an improper method for determining their merits; for (beside the ground of error now mentioned) a much greater quantity of light is reflected from gilt letters, than from those of common print on paper.

Hence, the excellence of an elliptic figure, for the smaller speculum of the Gregorian telescope.* But the case is very different, in a spherical or hyperbolic mirror. From either of these, the rays, which issue in a cone or pencil, from single, luminous, distinct points, in a very remote object, and fall on them, will not converge again, to so many single points; but will, in the mean focus of the mirror, be dispersed, and blended together in a small degree, yet sufficient to produce an universal haziness and indistinctness, over the whole surface of the object viewed in a telescope, having its large mirror of these forms, because it occurs, with respect to every point in such object; of which the following are the circumstances.

---

* But this will not be the case, if the rays diverge from points, so remote from the axis of this speculum, as to make a considerable angle with it, and to fall very obliquely on the speculum: which would be the case, if the field of the telescope were too large, or if the focus of the great speculum were too long, with respect to that of the lesser concave one: because, in either case, the image, formed by the great mirror, which is the object, with regard to the lesser, will have too great latitude; and the extreme pencils, diverging from it, fall, with too much obliquity, on the latter, to be collected by it, to single points, in the second image. And, on this account, there is, in the Gregorian telescope, a limit set to the degree of magnifying, so far as this depends on the mirrors, be their figure ever so correct. And, if any aberrations prevail, in the image formed by the larger concave, they will be magnified by the lesser, were it perfect, in the proportion of the focus of the former to that of the latter. I am of opinion, that it is better not to aim at a high degree of magnifying, by the little mirror of this telescope; but, to endeavour to secure the correctness of the second image; and to lay the chief stress of the amplification (as it is in the Newtonian telescope) on the eye-glasses; because of the above circumstance, which no correctness, nor compensation of the mirrors, can remedy. From this inconvenience, here stated, the Newtonian telescope (the most perfect of all the constructions, that ever were or ever will be devised) is entirely free. This the author effected, by putting the eye-glasses on a different axis from that of the mirrors; by which he was enabled to make the lesser mirror a plane surface. And it will appear, on due consideration, that he was obliged to introduce this change, in Gregory's telescope, of necessity; and not from a low ambition, to which his mind was superior, that of obtruding his own inventions, to supplant those of equal merit by other men: though he has not stated all the imperfections of the Gregorian form, nor the advantages of his own; having only, in answer to objections, and, as it were, reluctantly, mentioned the chief circumstances, justifying the alteration he had recommended.

If the mirror be spherical, those, rays, nearly parallel of each pencil, which fall on it, next to its center, will converge to a point more distant from the mirror, than the focus of any rays, that fall between the center and outer edge of the mirror. And those, that fall on the outer extremity of it, will converge to a different point, nearest to the mirror: and the rays, which are incident on the several concentrical annuli, indefinitely narrow, of which the face of the mirror is composed, will have an indefinite number of points of convergence; each annulus its own point, and all lying in a series, in the axis of the pencil, between the points, or foci, of the extreme, and of the innermost annulus.* So that no entire incident pencil will, after reflection, converge to one point, unless the radiant point were in the center of curvature of the mirror.

---

* This property of a spherical mirror has never, so far as I know, been synthetically demonstrated, by any optic writer, though it is a fundamental theorem in catoptrics. Mr. Robins derisively objected to Dr. Smith, that he had

The property of an hyperbolic mirror is of the same nature, but with effects reversed: for, in this, the rays parallel to its axis, which are incident on its outer annulus, will converge to a point the most distant from it; and the rays, falling on its innermost annulus, will have their focus the nearest to it. And this is easy to comprehend: for, as the curvature of the hyperbola continually diminishes from its vertex, on each side, a parallel, or diverging pencil, falling at a distance from the vertex, on a mirror of this form, must (as in the case of a mirror of greater radius, i. e. of less curvature) have its focus formed farther from it, than if it were incident near the middle or vertex, where the curvature of the mirror is that of a circle of lesser radius.

And thus it is evident, that, as the several pencils, reflected by the great mirror, when it is spherical or hyperbolical, do not converge, each to a single point, but to a series of points, whose length is the depth of the focus of the mirror; so, neither do these pencils, in proceeding on to the little mirror, diverge each from a single point, but from the same series of points. So that, though

---

had not demonstrated it. The Doctor, I believe, might have retorted the same charge on Mr. Robins. I have some reason to think, it is difficult to give such a demonstration of it, and that it will reflect credit on the person who furnishes it.

though the little mirror were formed truly elliptical, it would not make each of these pencils converge again (at the place of the second image, formed behind the first eye-glass) to single points, but to another series of points; by which the rays of contiguous pencils would be blended with one another, and make the object which is viewed, by means of these pencils, so transmitted to the eye, and, by it, refracted to a third series of points, near the retina, at the bottom of the eye, appear hazy and indistinct.

These remarks will be applied to our present purpose, by considering:

First. That the rays, reflected by the several annuli, in the surface of the great mirror, will fall on the annuli of the same order, in the little mirror; the rays from the outer, inner, or intermediate annuli of the one, proceeding to the like annuli in the other.

Secondly. That the farther the focus, or point of convergence, of any annulus of the great mirror, is distant from that mirror, the nearer will be the point of divergence of this part of the whole pencil, (among the series of such points), to the little mirror. Also, that the interval, between any one point in the series and this mirror, cannot be altered, by moving the mirror, without altering the intervals of all the rest; which, after the telescope is brought to the distinctest vision, cannot be permitted.

Thirdly. That, if the focus of any annulus, of the great mirror, be farther from it, than those of the other annuli,

nuli, and, consequently, nearer to the little mirror than those; the rays, issuing from it, to this mirror, will not be reflected by it, to the same point with those of the other annuli, unless the curvature of the corresponding annulus, of the little mirror, be encreased, in the proportion of its radius to that of the great mirror: for, then only will the focus of rays, reflected by this annulus of the little mirror, be shortened, as much as, by the effect of that of the same annulus, of the great mirror, it would otherwise be lengthened. The same is true, vice versâ, if the focus of any annulus, of the great mirror, be shorter than those of the other annuli.

Fourthly. That, if there be any excess or defect, in the curvature of the great mirror, from that of a parabola, (and, consequently, a contraction, or elongation, of the foci, of the extreme rays of the reflected pencils,) there is no remedy, while this remains, but to make the little mirror so much deficient, or excessive in curvature, from that of an ellipse, (and, consequently, to lengthen or contract the foci of the extreme rays of the pencils reflected by it,) as its focus is, in proportion to the focus of the great mirror; there being no other means of reducing all the rays, of each pencil, to one point, at the second or conjugate focus of the little mirror: by which alone, the second image, consisting of such points, can be formed, and viewed distinctly, through the last eye-glass.

From all which, it is manifest, that, if the curvature of the great mirror be hyperbolical, or deficient, then that of the little mirror ought to be spherical or excessive; and, if the great mirror be spherical, the other must be parabolical or hyperbolical, according as its focus is long or short, in respect of that of the great mirror.

Should the telescope be faulty, from indistinctness of vision, it may be corrected, by altering the figure of either of the mirrors, as shall be most practicable. And, to know what the alteration should be, the method, directed by Mr. Mudge, may be followed, of excluding the light from the central, middle, or extreme zone of the great mirror, by fixing, on the mouth of the tube, three annular diaphragms of pasteboard &c., answering, in size and shape, to these zones respectively; by removing any of which diaphragms, the light will be admitted to the corresponding part of the mirror. If, then, by help of the adjusting screw, the object be first viewed distinctly, when the inner or central zone, only, of the mirror is uncovered to the light; and it be necessary, afterward, when it is seen by means of the exterior zone only, to remove the little mirror farther from the great one, (by turning back the adjusting screw,) in order to distinct vision: then one, or both of the mirrors, is deficient in curvature, i. e. the great one is hyperbolical, or the small one parabolical. And, on the contrary, if it be necessary, in this process, to bring the little mirror nearer to the great one; then one or both of the mirrors is spherical. For, in the former case, it is plain, that the mean focus of the outer zone of the little mirror is nearer to the second eye-glass, than that of the inner zone; since it is necessary to withdraw that focus, by putting back the little mirror: and the contrary is evident, in the latter case. The former could happen, only by the focus of the extreme rays, of each single pencil, being too far from the great speculum, (i. e. from its being hyperbolical,) and too near to the little one; or from the latter being deficient in curvature, near its edges; and thus throwing the focus of the rays, that fall there, too far from it, and too near to the last eye-glass. The second effect could arise only from a figure of the mirrors, the reverse of this. In the Newtonian telescope, there can be no doubt, where the defect of curvature is, because it has but one concave mirror.

When it has been thus determined what the defect is, means must be employed to correct it; and it may be expected, that, unless some certain mode, of effecting a different curvature of the great mirror, from that of the little one, is discovered, and skilfully practiced, there will be but few good telescopes, of the Gregorian form, constructed. For, if both mirrors be polished, in the same manner and method, it is likely, that the defects in their figure, and the species of their curvature, will be the same in both. Whereas, it has been shewn, that all these ought to be directly contrary in one, from what they are in the other; referring to the parabola and ellipse, as the standard degrees of curvature.

Now.

Now, the circumstances, which, in the method of polishing above-mentioned, have a tendency to produce particular species of conoids, have been already explained, and need not be repeated. But, as to the means of altering any figure already given, to the great mirror, in the Newtonian telescope, or to either of the mirrors in the Gregorian, which happens to be unsuitable to the other one; I have to observe, that, in my trials, I have found this could be effected on the polisher, without putting the metal to be ground again upon the hones. For if it has, at first, been formed to a tolerably correct figure, of any species, then a very small reduction, of the substance of the metal, will produce a sufficient alteration of its form. If the change required consists in a diminution of curvature, a continuation of the process, under the regulation before-mentioned, will, without any alteration of the polisher, generally, be sufficient to produce it, from the degree of curvature of a circle, to that of the ellipse, parabola, or hyperbola, in order; or from any of these, to the others, in succession.* But, if the degree of curvature, already given, is to be increased, and to verge more towards the circle, as the limit, (beyond which no contrivance could carry it,) then the polisher must undergo an alteration. Its breadth should be diminished; the space, at the center, left uncoated with pitch, should be greatly contracted; and, in the case of the little mirror, which has no perforation in it, entirely filled up; save that a small hole, through the polisher, tapering, from the back of it, upwards, to its surface, should be left, for the pitch to sink into, when it becomes closed, and too much compressed, at the center; and the furrows, in the pitch, gradually deepened towards the edges. I believe, that (for the reason before given) the uncoated space, at the center, ought always to be as much smaller, on every side, than the perforation in the mirror, as the greatest range of the strokes, in polishing, advances the center of the mirror beyond that of the polisher, having the same shape as the polisher itself; and that it ought to be smallest, or no other than as just mentioned, when there is no hole in the mirror.

---

* Here it may be proper to observe, that, as the curvature is constantly diminishing, by the mere continuance of the operation, so the process is not to be pursued any longer, after the polish, and the desired figure, are found to be perfected. And the metal must always be brought to a very fine face, and a correct spherical figure, on the hones, or on a leaden tool, bedded with the finest washed emery, before the process of polishing commences: because, if all scratches, from the grinding, be not previously obliterated, the polishing must,

I have,

---

must, in order to efface them, be continued so long, as to diminish the curvature of the mirror beyond what is requisite; especially, if the area of the polisher be not of an oval, but of a round shape; which latter has a greater tendency, than the former, to diminish the curvature of the mirror, and to render it hyperbolical. And the correction of this, afterward, might require a troublesome alteration of the polisher, or even make it necessary to put the metal again upon the hones: and yet, in the Gregorian telescope, the hyperbolic figure is the proper one, for either of the mirrors, if that of the other speculum be spherical.

I have, in this method, with certainty of success, as verified by examination of the progressive change of curvature in the mirrors, from a greater degree to a less, and vice versâ, effected the desired configuration of them: which serves to confirm me in the belief, that the circumstances, above proposed, are those which are really operative, in communicating the diversity of figure to telescopic mirrors; and that neither the direction of the strokes in polishing, the size or form of the polisher, consistence of the pitch made use of, or other accidents, are of any farther moment in the process, than as they serve to modify the resistance of the pitch, in the several parts of the surface of the polisher. Whether, by attention to the principles here laid down, it would be possible to produce an hyperbolic form, in the convex mirror of the *Cassegrain* telescope, I have been prevented from endeavouring to ascertain by experiment, from those casualties, affecting my situation in life, which I have already intimated. But it should seem, that it would, to a certain degree, be practicable, from the means I have suggested, of producing a progressive, specific alteration in the figure of the polisher; if I have judged rightly of the existence and cause of that alteration.

And if it should be found possible to give, to a convex speculum, an hyperbolic curvature, the same could be done to the convex object glasses of dioptrical telescopes: which is a property still wanting to them; a want which makes them inferior to reflectors, even when they have been rendered achromatic, if the aberrations from their spherical figure remain, after those from refrangibility are removed: which aberrations, taken laterally, as they always ought to be, are as the cubes of the apertures. So that, if the lineal aperture be doubled, and the light admitted, which is as the square of the aperture, quadrupled, in order to increase the magnifying power four times, (or to double the lineal amplification,) preserving an equal brightness in the image; the telescope must be made four times longer, that it may remain equally distinct;* an inconvenience, from which it must be very desirable to exempt this telescope, by correcting the figure, and, with it, the aberrations of its object glasses.

It is not the object of this essay, to investigate any particulars, in the construction of the telescope; (which would open a large field of enquiry;) but to try to assist mechanical contrivance in its fabrication. To this end, I think it fit to add a remark, on the property of the pencils of rays, respecting the latitude of each of them, where they fall on the pupil of the eye; first discovered by the great Mr. Huygens: as I suspect, that the inconvenience he mentions, as resulting from a certain breadth of the pencil, may casually exceed the limit stated by him, and may admit of a practical remedy.

---

* A conception of this may be, perhaps, most familiarly acquired, by considering, that if, of two object lenses, the aperture, and also the focus of one, be twice as great as those of the other, the angles of incidence, and refraction, of the extreme rays, which come from a very remote object, and form the cones or pencils made by both, will be equal; and the pencils themselves, and their aberrations, will be similar figures; all the lineal measures of that of the larger lens, being double those of the other. In order, therefore, to reduce the lateral error or diameter of the circle of aberrations of the former, to an equality with that of the latter, while the aperture, which is the base of the pencil, remains double; this pencil must be made twice more narrow or acute than before. And, to effect this, its length or focus (which, at first, was twice as great as that of the other pencil) must be doubled; so that now it must be four times as long as the smaller pencil: i. e. the lengths should be as the squares of the apertures.

He observes, that if the latitude or breadth of the pencils, at the pupil of the eye, be very small, (so as not to exceed, if I remember right, the sixtieth part of an inch,) the vision, by the telescope or microscope, will be indistinct; so that, unless the pencils be of greater breadth than this space, at the place of the eye, the instrument will be defective: and he attributes this to something in the natural conformation, or in the humours of the eye; which, consequently, will admit of no remedy. On this may I presume to observe, that the latitude of the pencil, as it enters the eye, is the same as that with which it falls on the last eye-glass; and, that the effect of it, which Mr. Huygens attributes to the eye, may, therefore, as naturally, be attributed to the eye-glass, as to the eye; especially when an anatomical dissection of it will demonstrate, that the perfect transparency of its humours, and exquisite polish of its cornea, or outer coat, (not to talk of its achromatic property,) far exceed, in this optic instrument of the Deity, any thing that can be manufactured by man. In fact, the polish given to the eye-glass, and the transparency of the glass itself, is always imperfect; and many points in its surface, which ought to serve for the regular transmission of light, will be obstructed by its roughness and opacity: so that, if the pencils occupy but a very little space on the lens, no points of fair transmission may there remain; and the few rays, that pass through, may be so distorted, by irregular refraction, and inflection, in the glass, and in the eye-hole, that the vision must be indistinct. And this was the more likely to happen, in Huygens's time; because, neither the fine polishing powder, of colcothar of vitriol, was then in use; (and Mr. Huygens used nothing but tripoli;) nor was the method of polishing, by the help of pitch, divulged by Sir Isaac Newton. If this conjecture be right, the remedy is, to use both these helps, in communicating an exquisite polish to the eye-glasses; especially the smaller one, where the breadth of the pencils is reduced, in the same proportion as its radius, or as the increase of its magnifying power: and, also, to avoid using flint glass for this purpose; as it is found to be the least transparent of any, as well as most dispersive.

I may here also observe, that, as the transparency and polish of glass must ever be, to a certain degree, imperfect; so the projected improvement of Mr. Ramsden, to avoid the dispersion of the rays, by throwing the image just before the first eye-glass, is unlikely to answer: because, in this case, each of the pencils would occupy little more than a point, on the surface of the lens; and, if that point should be opaque, or unpolished, or covered with dust, no rays of the whole pencil could be transmitted through it: which would, probably, happen to too many of the pencils, and affect the image, which is composed of these pencils; whose latitude, therefore, ought to be greater than the limiting measure stated by Mr. Huygens. And, to effect this, with as high a charge as the instrument will bear, a part of the amplification should be thrown away, on the first eye-glass, and diminished, by shortening its focus; that the pencils being, by it, rendered more obtuse, may fall, with greater divergence, and latitude, on the second eye-glass, which may thus be made shorter, and on the eye. For it is not to be supposed, that the image, formed in a telescope, can be viewed, by a small lens, with as much advantage as an object may. The rays, from each point of the latter, fall upon the whole surface of the lens; and, therefore, a sufficient number of them, to fill the pupil of the eye, must be transmitted: whereas, the rays, from each point of the image, occupy only a small speck on the lens; in no case larger, in effect, than the pupil of the eye: and must, when so contracted, be the more obstructed, by any imperfections in the glass.

As, therefore, the fineness of the powder, employed in giving the highest lustre and polish to the specula, and to the eye-glasses, is of great importance, in that process: and, as I found, that the crocus, or colcothar of green vitriol, (now used, as the fittest for that end,) could seldom be procured, so free from grittiness, as to be capable of levigation, to a sufficient degree of fineness; insomuch, that I was obliged to attempt to make it myself: it may be useful to state, that, by the following easy method, I succeeded in producing some of excellent quality.

Considering that the vitriol, distilled in close vessels, might probably contract this grittiness, in its calx, from an union of some of its component parts, or principles, with the water contained in the vitriol, (which is the metallic salt of iron,) and that this might prevent its perfect calcination; I thought it best to perform the distillation in the open air, and to begin with exhaling the water. Accordingly, I commenced with slowly roasting the vitriol or copperas, broken into grains as small as shot, by holding it over the fire, on a fire-shovel, till the moisture in it appeared to be dried away. I then put it into a crucible, and kept it uncovered, in a clear fire, till it had been some time red hot;* by which, the spirit or oil of the vitriol was distilled from it, and the calx or colcothar remained, of a brownish red colour, and of a perfectly equal texture, entirely free from hard or gritty particles: and it was easily levigated, when moistened with water,

on

---

* I suppose that the fire ought not to be too high, or too long continued, in this process, lest it should convert the calx of the iron into glassy scoria. Experiments will determine the due regulation of the heat, so as to ensure success to the operation in every instance. The heat ought to be so great, as to give the colcothar, not a brown, but a red colour.

on a piece of looking-glass-plate, by a piece of the like glass having a handle of brass cemented to it. This furnished a very fine and impalpable powder, capable of communicating to the specula, or lenses, the most exquisite polish and lustre.*

To apply with precision, and afford a fair trial of the method of polishing I have recommended, it is necessary farther to consider, that the advantages, resulting from correctness of figure, in the mirrors, may be frustrated, by an undue position of them, or of the lenses, in the instrument, or by a defect of form in the lenses, whose edges may happen to be thicker on one side than on the other; i. e. they may not be complete, or equally curtate segments of spheres; and, consequently, that a proper trial and estimate cannot be made, of the figure of the mirrors, unless these and the eye-glasses be right in these respects; especially in the Gregorian telescope, whose adjustment is a matter of more nicety and difficulty, than that of the Newtonian. And since, in the former, the surfaces of the mirrors and lenses ought all to have one and the same axis, viz. that of the instrument, in which are to be all their foci; it is necessary this should be cautiously ascertained: because contrary deviations of them, in this respect, might apparently compensate one another, and escape detection, though they would really be attended with the aberrations of enlarged apertures.

---

* The same powder, spread on leather, would give the smoothest edge to razors and lancets, &c.

The center of the great mirror ought to be in the common axis of the instrument; and the position of it in its cell, in the tube, may be known thus. Let the little mirror be taken out of the tube; and let the round, central diaphragm, before-mentioned, (which ought to be made of a flat piece of tinned plate, or a brass plate, made clean and bright enough, to reflect the light strongly, but not polished,) be fastened across the mouth of the tube, exactly in the middle of it; and let a round hole be made through the plate, the center of which shall be in the axis of the tube, and its diameter so large, as that the whole disc of the sun may be viewed through it, at the eye-hole of the telescope, when the eye-glasses are taken out. Then, directing the instrument to the sun, or the full moon, when very bright, so as that its whole disc shall be seen through the hole in the diaphragm; (using a lightly tinged screen-glass, to look at the sun;) if the light, reflected from the great mirror to the diaphragm, occupies on it, a circular area, concentrical with the hole made at its center, the mirror is rightly placed, and its focus is in the axis of the tube. But, if the edge of the illuminated circle approaches nearer to the hole in the plate, on any side, the same side of the mirror inclines toward the axis of the tube, its cell not being exactly vertical to it; or otherwise, the center of the mirror is not in that axis, as it ought to have been. If the outer one, of the three aforesaid diaphragms, be, at the same time, applied to the mouth of the tube, so as to expose only the middle zone of the great mirror to the light; the circle of light, reflected by it, to the central diaphragm, will appear better defined on it.

But the adjustment of both mirrors and lenses may, at the same time, be proved, by the following most easy and certain method, if exactly pursued.

Having provided, that the little mirror shall be so supported, that its center may always move in the axis of the great tube; and proved that it is so, as Mr. Edwards prescribes, by taking off the mirror, and seeing, through the eye-tube of the telescope, (without the lenses,) that the hole, in the middle of the little round plate, to which that mirror is screwed, concentrical with the plate, corresponds with the intersection of two cross hairs, tied diametrically across the mouth of the tube: then let the little mirror be replaced, and the eye-tube taken out, and let the telescope be directed to the sun's center; which may be done, by the help of the little dioptrical telescope, called *a finder*, affixed to the instrument, if it be furnished with such; or otherwise, may be effected, with sufficient exactness for this purpose, by pointing the telescope to the sun, so as that the shadow of the little mirror may coincide with the hole, in the great mirror; which will be, when the great tube is so placed, as to project its shadow of a circular form. In these circumstances, let the light, reflected from the little mirror, through the round perforation in the great one, be received upon a plane, placed at some distance behind the latter, at right angles to the axis of the tube. The light will occupy a circular area on the plane; and, if the center of the light be coincident with that of the shadow of the little mirror, this mirror is not only parallel to the great one, but both are duly adjusted, at right angles, to the axis of the tube; which, also, then corresponds with their axes. But, because the little mirror and its shadow, and also the cone of light, reflected from this mirror, are of greater breadth than the perforation in the great one; the boundaries of the reflected light, and those of the shadow, cannot be seen wholly on the plane, through the hole in the great mirror, in any one position of the telescope. Let, therefore, the axis of the telescope be a little diverted from the center of the sun, till the shadow of the edge of the little mirror falls within the hole in the great one: by which, some direct light will pass through, next the shadow, and appear on the plane, in form of a crescent; and, at the same time, the circle of the reflected light of the sun will have moved across the shadow: till, by a certain degree of obliquity, in the direction of the telescope, the edge of the circle of the reflected light will be in contact, externally, with the crescent of the direct light. And, if the crescent be always of the same breadth, when this contact takes place, on every side, by a diverting of the telescope, from the center of the sun, successively, in every direction; then both the mirrors are parallel, and at right angles, to the axis of the instrument. But, if the crescent be broader, in any certain position of the tube, when the circle of reflected light just touches its edge: then the side of the little mirror, corresponding with that of the illuminated circle, where it is in contact with the crescent, makes too great an angle, with the axis of the instrument; and it must be reduced to a right angle, by screwing forward the adjusting screw of the little mirror, in that part, having previously withdrawn the opposite screws. When the mirrors are thus found to be rightly placed, and the eye-tube and lenses are restored to their places; if the whole image, of the great mirror, be not visible in the eye-hole, when this is in the common axis of the instrument, then the lenses are defective: either, some of them, or some of their surfaces, or the tube they are fixed in, being inclined to the common axis; and, by this means, distorting the cone of rays, from it. Which irregularities must be rectified, before a true estimate can be formed, of the correctness of the mirror's curvature.

The distance from the smaller lens, at which is the point of decussation of all the pencils of light, and the place where the eye-hole ought to be, may also be most easily and most accurately found, by directing the telescope to the sun, having taken off that part of the eye-tube behind the lenses; and letting the light fall on a plane, moveable back and forward, behind the second eye-glass, and kept at right angles, to the axis of the specula and lenses: the place, at which the image of the great mirror, with the shadow of the little mirror described on it, is seen most distinctly formed on the plane, ought to be the place of the eye-hole.